MULTIVARIATE MODELS UTILIZE ACCELEROMETERS TO ESTIMATE PEAK VERTICAL GROUND REACTION FORCE

HONORS UNDERGRADUATE RESEARCH THESIS

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Abstract

Three-dimensional (3-D) motion capture is a valid method to quantify human motion, yet requires expensive equipment and a specialized laboratory not available in a clinical or athletics environment. Tri-axial accelerometers pose a portable, cost-effective solution to analyze human motion. Previous research indicates that accelerometers can predict peak vertical ground reaction forces (vGRF) during low-impact tasks, but these units have not been validated for dynamic, high-impact landings. The objective of this study was to develop a multivariate model that utilized anthropometric measures and peak accelerations to estimate peak vGRF during dynamic jumping tasks. Ten healthy subjects were recruited for the study. Activity monitors were secured bilaterally to the foot, medial tibial surface, lateral femoral epicondyle, and midpoint between the right and left anterior superior iliac spine. Subjects performed 10 drop vertical jump tasks and 10 bilateral single leg drop tasks off a 31cm tall box onto two floor embedded force plates. All tasks were performed during continuous collection of 3-D motion capture data and tri-axial accelerations. Peak vGRF was extracted from motion capture data for each DVJ and SLD trial. Peak acceleration was extracted from tri-axial acceleration data. Multivariate linear regression models that incorporated anthropometric data and peak acceleration magnitudes were separately developed to predict peak vGRF for DVJ and SLD trials. Height, weight, peak waist acceleration, and peak thigh acceleration were significant predictors of vGRF during a DVJ task. Peak waist, thigh, and shoe

accelerations were significant predictors of vGRF during a SLD task. The correlations between recorded vGRF and predicted vGRF for both DVJ and SLD trials were significant (DVJ: $R^2 = 0.7451$; SLD: $R^2 = 0.7266$). Models that utilize anthropometric data and activity monitors to accurately predict vGRF provide a cost-effective method to collect human motion data. This study is the first to our knowledge to utilize multiple activity monitors to produce these results during dynamic, high-impact landing tasks. Future work will attempt to validate activity monitors to measure lower extremity kinetics and kinematics during multiple dynamic tasks.

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INTRODUCTION

Three-dimensional motion capture (3-D MOCAP) is a valid method to quantify human motion. 3-D MOCAP incorporates both infrared cameras to track the trajectories of retro-reflective markers placed at anatomic and tracking landmarks on the body and floor embedded force plates to record ground reaction forces throughout each collection. From these data, inverse dynamics is employed to calculate segmental kinetics and kinematics to study human movement strategies. One application of 3-D MOCAP is to study and measure risk of anterior cruciate ligament (ACL) injury. [6, 11] ACL tears account for significant time lost from athletic participation, and over 30% of athletes never return to active participation in their sport. [1, 26] In order to return to sport following ACL reconstruction, athletes must complete rigorous post-surgery physical therapy. However, functional and strength impairments can persist after treatment, which can increase the risk of a secondary injury. [23] Therefore, it is critical to identify risk factors in order to prevent the long-term, deleterious consequences of repeated ACL injury.

While 3-D MOCAP effectively identifies those at elevated risk for non-contact ACL injury, these techniques require expensive equipment, a specialized laboratory, and regular maintenance that are not available in a clinical setting. Alternative portable methods are desired to quantify similar human motion in a clinical or athletics environment for personnel that cannot afford or employ 3-D MOCAP techniques. Tri-axial accelerometers pose a portable, low-cost solution to analyze human motion; thus, these devices have been targeted as an effective method to study biomechanics in a clinical setting. [5, 12, 14, 25, 27] Previous research indicates that accelerometers can predict peak vGRF during low-impact tasks, such as gait and running, but the use of these units to model ground reaction forces in more dynamic tasks is largely unvalidated. [21, 24, 28]

The objective of this study was to develop a multivariate model that utilized anthropometric measures and peak accelerations to estimate peak vGRF during dynamic jumping tasks. We hypothesized that a model created with significant anthropometric and peak acceleration predictors from a multivariate linear regression would significantly correlate to peak vGRF collected with 3-D MOCAP techniques.

METHODS

Subjects

Ten athletic subjects (males = 6, females = 4; age: 21.1 ± 1.1 years; height: 1.72 ± 0.10 m; mass: 68.83 ± 14.09 kg; BMI: 23.09 ± 3.27 kg/m^2) were recruited for this study. All subjects perform greater than 50 hours of athletic activity a year. All subjects provided informed consent approved by The Ohio State University Institutional Review Board before participating in the study.

Procedures

Each subject was instrumented with 55 retro-reflective markers. Activity monitors developed at Mayo Clinic (Rochester, MN) were secured bilaterally to the foot, medial tibial surface (shank), lateral femoral epicondyle (thigh), and midpoint between the right and left anterior superior iliac spine (waist) (Figure 1). Accelerometer position was randomly matched with an accelerometer before each subject trial. Each monitor incorporated a tri-axial MEMS accelerometer (±16g, 100Hz, Analog Devices).

Subjects performed 10 drop vertical jump (DVJ) tasks and 10 bilateral single leg drop (SLD) tasks off a 31cm tall box onto two floor embedded force plates that recorded ground reaction forces at 1200Hz. Subjects performed two practice trials before each task. To perform a successful DVJ trial, the athlete stood on top to the box, dropped off the box, landed on both feet, and immediately performed a maximum vertical jump (Figure 2). Each DVJ trial utilized an overhead target beyond the reach of the athlete. For the SLD, the athlete stood on one foot on top of the box, hopped forward, landed on the same limb, and regained balance prior to completion of the task. All tasks were performed during continuous collection of 3-D MOCAP data and tri-axial accelerations. 3-D MOCAP consisted of 12 cameras collecting at 240Hz (Raptor cameras, Motion Analysis Corporation, Santa Rosa, CA) connected through an Ethernet hub to a Dell desktop computer (Dell Computers, Los Angeles, CA).

Data Analysis

Peak vGRF from initial contact was normalized to subject body mass and was extracted from motion capture data for each DVJ and SLD trial. Tri-axial acceleration data were extracted from each accelerometer. Acceleration data were filtered through a median filter to smooth data and remove noise as well as a low pass filter to remove the gravitational acceleration component.[8, 15] Extraction and filtering were completed using MATLAB software (MathWorks, Natick, MA). Continuous acceleration magnitude was calculated from tri-axial acceleration data. The peak acceleration at initial impact was manually extracted for each DVJ and SLD trial from the continuous acceleration magnitude data. Individual trials that did not have continuous vGRF data or acceleration data from all seven activity monitors throughout the task were excluded from the study.

Multivariate linear regression models that incorporated anthropometric data and peak acceleration magnitudes were separately developed to predict peak vGRF for DVJ and SLD trials. R-squared (R^2) values were calculated for each model. Both the DVJ and SLD multivariate models only included significant parameters. Statistical analysis was conducted using SPSS™ statistical software (IBM Corporation, Armonk, NY). Statistical significance was set *a priori* at $\alpha = 0.05$.

RESULTS

Height, mass, peak waist acceleration, and peak thigh acceleration were significant predictors of vGRF during a DVJ task (Table 1). Peak waist, thigh, and foot accelerations were significant predictors of vGRF during a SLD task (Table 1). The correlations between recorded vGRF and predicted vGRF using multivariate regression predictors for DVJ and SLD trials were significant (DVJ: $R^2 = 0.7451$; SLD: $R^2 = 0.7266$) (Figures 3-4).

DISCUSSION

A model using height, mass, peak waist acceleration, and peak thigh acceleration from a multivariate regression analysis can predict peak vGRF with an excellent R^2 value during DVJ trials. A model using peak waist acceleration, peak thigh acceleration, and peak foot acceleration can predict peak vGRF with an excellent R^2 value during SLD trials.

Models that utilize anthropometric and acceleration data to accurately predict vGRF provide a cost-effective method to collect human motion data. Currently, researchers must utilize 3-D MOCAP in a laboratory setting to accurately study human kinetics and kinematics. 3-D MOCAP data collections are not only expensive, but are often difficult to schedule due to the demanding schedules of elite athletes. However, a portable method to study human biomechanics would allow researchers to measure kinetics and kinematics of athletes on the field. This would eliminate the necessity to study athletes in the lab and decrease scheduling conflicts. Furthermore, research laboratories that cannot afford or do not have access to 3-D MOCAP equipment can also begin to analyze potential risk factors in local athletic populations.

Although 3-D MOCAP accurately measures human kinetics and kinematics, the laboratory setting does not allow athletes to perform natural cutting and jumping tasks that occur during competition. In football, intensity varies between activity levels, exemplified by an injury rate over nine times greater during games than during in-season practices. [4] Because noncontact injuries occur rapidly during athletic competition, researchers have created dynamic tasks to mimic such events in a laboratory. [13, 22] The DVJ task is widely used to imitate the motion a basketball athlete undergoes while exploding vertically to rebound a basketball. [7, 11, 20] The SLD task is also used to imitate single leg planting during athletic activities. [19] However, these tasks only mimic the actual dynamic movements athletes undergo during injury. Portable activity monitors that can predict vGRF with acceleration data are the first step to quantifying human motion during the actual sport-specific tasks athletes perform prior to injury.

Clinicians can incorporate testing with activity monitors into current screening strategies conducted both in and out of athletic seasons. Researchers are currently expanding the array of portable tests clinicians can use to judge individual athletic performances as well as the effect of training interventions on those performances. Newer tests include timed hop tests, hop tests for distance, and tests that assess functional movement.[2, 3, 9, 10] However, no tests are currently used to test the forces in the lower extremities of athletes during dynamic tasks. The ability to quickly and accurately measure ground reaction forces with activity monitors will provide an additional portable method to assess athletic health.

Future work will incorporate sex and task differences into one model. While the current model predicts vGRF with excellent correlation to vGRF measured with 3-D MOCAP, the current statistics do not incorporate DVJ and SLD into one model. As future goals of the study include using activity monitors to measure forces during a variety of dynamic athletic tasks, the model used to predict vGRF must be able to incorporate multiple types of movements. Previous work with running and gait trials has utilized repeated measure mixed effects regression statistics.[21] Similar models for high-impact landings must be investigated. Repeated measure mixed effects models take into account the variation between tasks as well as the variation between subjects.

Understanding the variation between tasks will allow for the creation of a model that can be used to measure vGRF in multiple different dynamic tasks. Understanding the variation between subjects will provide insight about how to calibrate accelerometers and how to use those measures within the model.

Future work will also attempt to validate the portable measurement of moments in the knee joint using 2-D video analysis. Previous research has proposed 2-D video as a valid portable alternative to 3-D MOCAP in measuring frontal plane knee angles. [16-18] Knee angles and ground reaction forces are the two variables integral to calculating knee abduction angle, a known risk factor of ACL injury. [11] Calculating knee moments, however, might necessitate the use of accelerometers with gyroscopes. Positional information of the local activity monitor axis would allow calculation of triaxial accelerations in respect to the global coordinate system the embedded force plates within the 3-D MOCAP collection are using.

Limitations to this study include individual activity monitor malfunction. Certain activity monitors did not collect any acceleration data or collected saturated acceleration data sets, both of which caused the data to be discarded before the final regression analysis. In addition, the activity monitors did not contain gyroscopes, so it was not possible to relate the local axis of the activity monitors to the global axis of the embedded force plates and compare peak vertical acceleration to peak vGRF. Finally, these models need to be validated with disparate data sets.

CONCLUSION

Multivariate models that utilized anthropometric data and peak accelerations successfully predicted peak vGRF. This study is the first to our knowledge to utilize multiple activity monitors to produce these results during dynamic, high-impact landing tasks. Application of this model provides clinicians and performance specialists with an opportunity to expand the environment in which they can measure the forces created by athletes during dynamic tasks. Use of accelerometers could expand the research opportunities of what types of athletes are screened, when they are screened, and at what levels of performance. The long-term goal of the study is to validate the use of activity monitors to assess injury risk in a non-laboratory athletic environment while subjects perform sport specific tasks.

Figures and Table

Table 1: Multivariate regression results

	DVJ		SLD	
	β	phon	β	p
Constant	-.619	0.232	1.535	<0.001
Height	.923	0.012	Not Included	Not Included
Mass	-0.007	0.026	Not Included	Not Included
Peak Waist ACC	.123	<0.001	.045	0.035
Peak Thigh ACC	.058	<0.001	.088	<0.001
Peak Shank ACC	Not Included	Not Included	Not Included	Not Included
Peak Foot ACC	Not Included	Not Included	.024	0.002

Figure 1: Drop vertical jump task

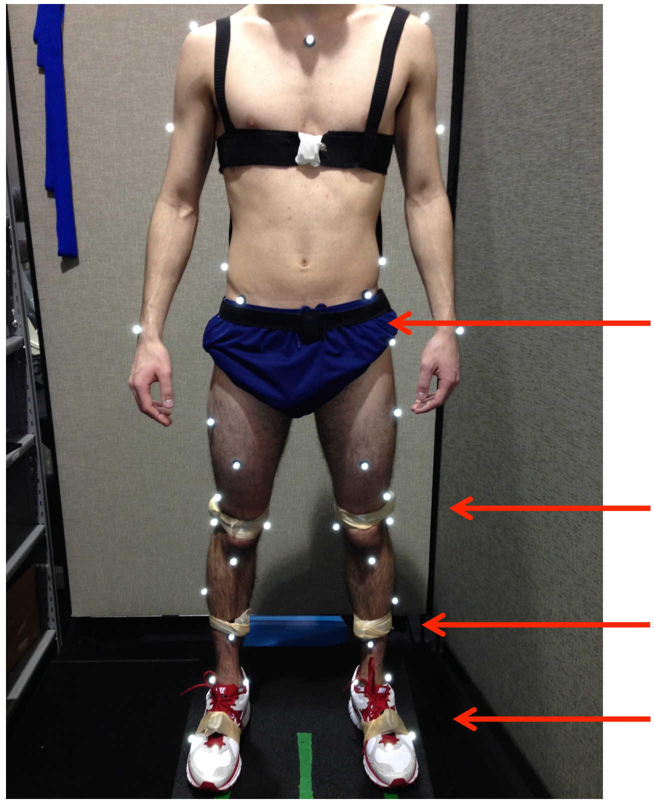

Figure 2: Activity monitor placement on subjects

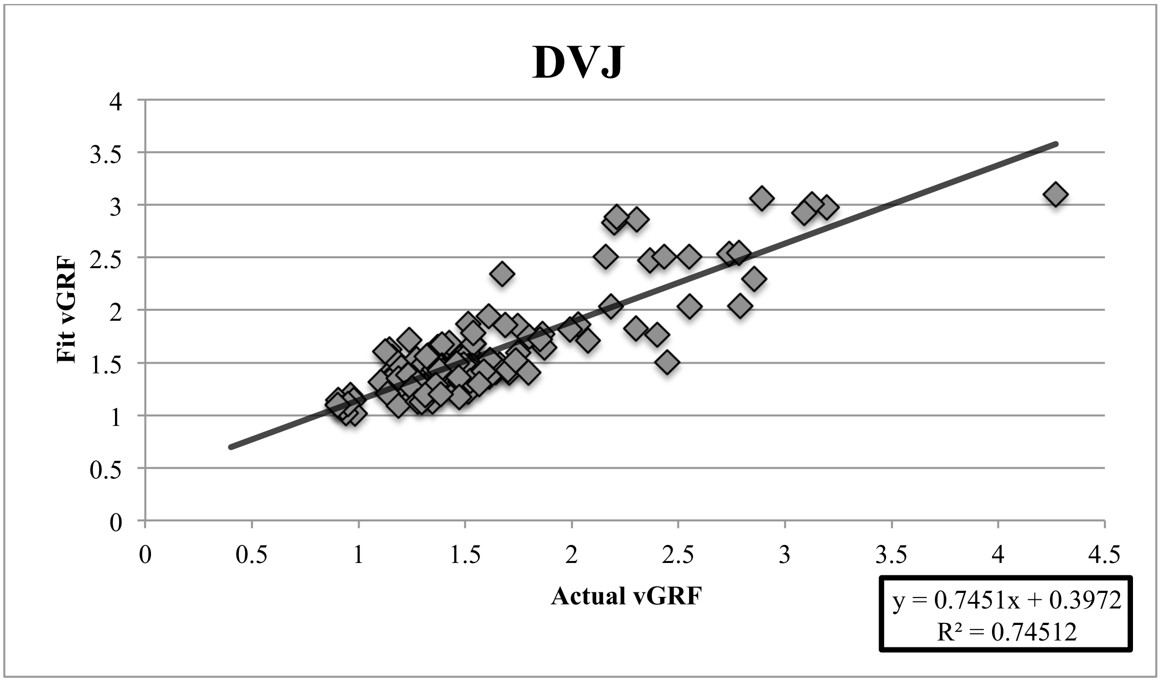

Figure 3: Fit vGRF vs measured vGRF using multivariate linear regression parameters – DVJ

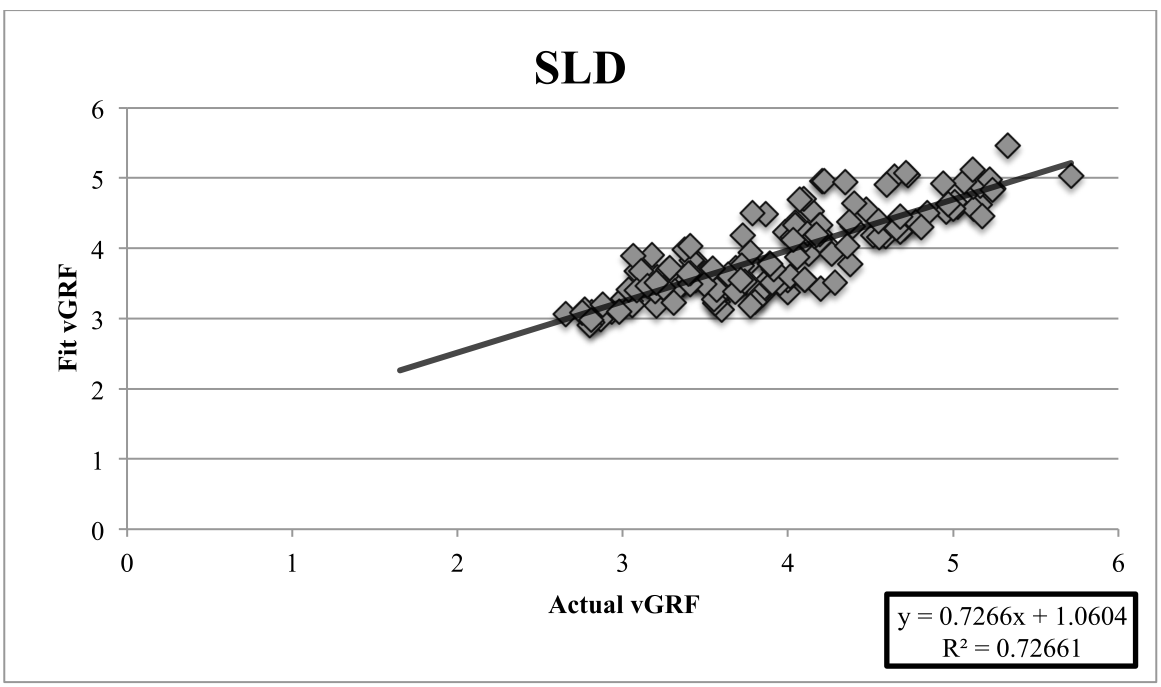

Figure 4: Fit vGRF vs measured vGRF using multivariate linear regression parameters – SLD

References

1. Ardern CL, Taylor NF, Feller JA, et al: Return-to-sport outcomes at 2 to 7 years after anterior cruciate ligament reconstruction surgery. *Am J Sports Med*. 2012*;40*(1):41-48.

2. Cook G, Burton L, Hoogenboom B: Pre-participation screening: the use of fundamental movements as an assessment of function - part 1. *N Am J Sports Phys Ther*. 2006*;1*(2):62-72.

3. Cook G, Burton L, Hoogenboom B: Pre-participation screening: the use of fundamental movements as an assessment of function - part 2. *N Am J Sports Phys Ther*. 2006*;1*(3):132-139.

4. Dick R, Ferrara MS, Agel J, et al: Descriptive epidemiology of collegiate men's football injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *J Athl Train*. 2007*;42*(2):221-233.

5. Dobkin BH: Wearable motion sensors to continuously measure real-world physical activities. *Curr Opin Neurol*. 2013*;26*(6):602-608.

6. Ford KR, Myer GD, Hewett TE: Valgus knee motion during landing in high school female and male basketball players. *Med Sci Sports Exerc*. 2003*;35*(10):1745-1750.

7. Ford KR, Myer GD, Schmitt LC, et al: Preferential quadriceps activation in female athletes with incremental increases in landing intensity. *J Appl Biomech*. 2011*;27*(3):215-222.

8. Fortune E, Lugade V, Morrow M, et al: Validity of using tri-axial accelerometers to measure human movement - Part II: Step counts at a wide range of gait velocities. *Med Eng Phys*. 2014*;36*(6):659-669.

9. Frohm A, Heijne A, Kowalski J, et al: A nine-test screening battery for athletes: a reliability study. *Scand J Med Sci Sports*. 2012*;22*(3):306-315.

10. Hegedus EJ, McDonough S, Bleakley C, et al: Clinician-friendly lower extremity physical performance measures in athletes: a systematic review of measurement properties and correlation with injury, part 1. The tests for knee function including the hop tests. *Br J Sports Med*. 2014.

11. Hewett TE, Myer GD, Ford KR, et al: Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. *Am J Sports Med*. 2005*;33*(4):492-501.

12. Hurd WJ, Morrow MM, Kaufman KR: Tri-axial accelerometer analysis techniques for evaluating functional use of the extremities. *J Electromyogr Kinesiol*. 2013*;23*(4):924-929.

13. Krosshaug T, Nakamae A, Boden BP, et al: Mechanisms of anterior cruciate ligament injury in basketball: video analysis of 39 cases. *Am J Sports Med*. 2007*;35*(3):359-367.

14. Lawinger E, Uhl TL, Abel M, et al: Assessment of Accelerometers for Measuring Upper Extremity Physical Activity. *J Sport Rehabil*. 2015.

15. Lugade V, Fortune E, Morrow M, et al: Validity of using tri-axial accelerometers to measure human movement - Part I: Posture and movement detection. *Med Eng Phys*. 2014*;36*(2):169-176.

16. McLean SG, Walker K, Ford KR, et al: Evaluation of a two dimensional analysis method as a screening and evaluation tool for anterior cruciate ligament injury. *Br J Sports Med*. 2005*;39*(6):355-362.

17. Mizner RL, Chmielewski TL, Toepke JJ, et al: Comparison of 2-dimensional measurement techniques for predicting knee angle and moment during a drop vertical jump. *Clin J Sport Med*. 2012*;22*(3):221-227.

18. Munro A, Herrington L, Carolan M: Reliability of 2-dimensional video assessment of frontal-plane dynamic knee valgus during common athletic screening tasks. *J Sport Rehabil*. 2012*;21*(1):7-11.

19. Myer GD, Bates NA, DiCesare CA, et al: Reliability of 3-Dimensional Measures of Single Leg Landing Across Three Different Institutions: Implications for Multi-Center Biomechanical and Epidemiological Research for Secondary ACL Injury Prevention. *J Sport Rehabil*. 2015.

20. Myer GD, Ford KR, Khoury J, et al: Biomechanics laboratory-based prediction algorithm to identify female athletes with high knee loads that increase risk of ACL injury. *Br J Sports Med*. 2011*;45*(4):245-252.

21. Neugebauer JM, Hawkins DA, Beckett L: Estimating youth locomotion ground reaction forces using an accelerometer-based activity monitor. *PLoS One*. 2012*;7*(10):e48182.

22. Olsen OE, Myklebust G, Engebretsen L, et al: Injury mechanisms for anterior cruciate ligament injuries in team handball: a systematic video analysis. *Am J Sports Med*. 2004*;32*(4):1002-1012.

23. Paterno MV, Schmitt LC, Ford KR, et al: Biomechanical measures during landing and postural stability predict second anterior cruciate ligament injury after anterior cruciate ligament reconstruction and return to sport. *Am J Sports Med*. 2010*;38*(10):1968-1978.

24. Rowlands AV, Stiles VH: Accelerometer counts and raw acceleration output in relation to mechanical loading. *J Biomech*. 2012*;45*(3):448-454.

25. Rowlands AV, Thomas PW, Eston RG, et al: Validation of the RT3 triaxial accelerometer for the assessment of physical activity. *Med Sci Sports Exerc*. 2004*;36*(3):518-524.

26. Shah VM, Andrews JR, Fleisig GS, et al: Return to play after anterior cruciate ligament reconstruction in National Football League athletes. *Am J Sports Med*. 2010*;38*(11):2233-2239.

27. Shim S, Kim H, Jung J: Comparison of upper extremity motor recovery of stroke patients with actual physical activity in their daily lives measured with accelerometers. *J Phys Ther Sci*. 2014*;26*(7):1009-1011.

28. Wundersitz DW, Netto KJ, Aisbett B, et al: Validity of an upper-body-mounted accelerometer to measure peak vertical and resultant force during running and change-of-direction tasks. *Sports Biomech*. 2013*;12*(4):403-412.